The Vital Role of Power System Studies in Microgrid Integration

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Executive summary

A microgrid is an integrated energy system consisting of distributed energy resources (DERs) that are controlled as a single entity in parallel with the utility grid or in off grid, islanded mode. The four primary drivers of microgrid implementation are (1) economics — reducing operational costs and increasing energy optimization, (2) sustainability — reducing carbon footprint through renewable energy generation, (3) resiliency — achieving electrical independence from the grid, and (4) infrastructure expansion — supporting new electrical loads when utility capacity is unavailable.

Many variables influence microgrid design, including selecting the optimal combination of DERs, evaluating existing infrastructure and planned load additions, and assessing multiple use cases to understand how the microgrid will perform. While operational goals guide DER selection and sizing, power systems studies are essential to ensure the microgrid functions as intended under different operating modes (grid tied and off grid) and across varying loading and energy generation scenarios.

Power systems studies verify DER sizing and identify potential failure points during microgrid operation. This white paper reviews the power system studies that are particularly important for microgrid applications and explains how they support reliable and resilient system design.

Glossary

Keywords	Abbreviations
Arc Flash	AF
Battery Energy Storage System	BESS
Coefficient of Grounding	COG
Combined Heat and Power	CHP
Distributed Energy Resource	DER
Electrical Transient and Analysis Program	ETAP
Inverter Based Resource	IBR
Low Voltage	LV
Medium Voltage	MV
Neutral Grounding Resistor	NGR
Photovoltaic System	PV
Point of Common Coupling	PCC
Power Electronic Loads	PEL
Power Factor	PF
Renewable Energy Sources	RES
Short Circuit	SC
Single Line to Ground Fault	SLG
Time Current Coordination	TCC
Time Domain Unbalanced Load Flow Analysis	TDULF
Total Harmonic Distortion	THD
Transient overvoltage	TOV
Variable Frequency Drive	VFD
Virtual Synchronous Generator	VSG

Introduction

Adding a mix of distributed energy resources (DERs), which can be either distributed generation or distributed storage, to a campus or building's electrical system may offer many benefits to the end user and help meet specific project goals. However, microgrid systems are unique, and each is designed to achieve specific objectives. Therefore, the design of a microgrid system also requires various power systems studies in addition to the standard short circuit, arc flash, and time current coordination analyses, to ensure the power system functions as intended. This document provides technical insights into **what** power system studies should be performed, recommendations on **when** they should be completed (both in terms of project development lifecycle and key drivers), and the expected **outputs**.

These studies include:

- Energy Analysis
- Short Circuit, Time Current Coordination, and Arc Flash Analysis
- System Grounding Analysis and Studies
- Load Flow and Time Domain Unbalanced Load Flow Analysis (TDULF)
- Black Starting, Transformer Energization, and Motor Acceleration Studies
- Transient Stability and Advanced Studies
- Power Quality and Harmonics Analysis

Designing any microgrid system requires the design engineer to have a thorough understanding of the system load profile that will be served by the microgrid. Fully understanding this load requires an **energy analysis** to be performed for the existing system. In cases of new construction, several reasonable engineering assumptions must be made based on an understanding of how the facility will operate and the anticipated electrical requirements. Using these assumptions, the engineer will create an anticipated load profile for the facility. Whether developed from existing data or forecasted assumptions, the energy analysis study is an integral part of the preliminary basis of design for the microgrid. The resulting load profile allows the microgrid design engineer to determine two key design factors: the overall energy (kWh) required and the maximum instantaneous power (kW) required.

Depending on the importance of each of the four microgrid drivers (economics, sustainability, resiliency, and expansion), the **engineer will size the appropriate DERs based on the priority of each and the project's specific objectives and goals**. For example, if economics is the primary driver, DERs may be slightly undersized to support more efficient operation by enabling higher utilization. Conversely, if resiliency is the priority, DERs are typically oversized to allow greater flexibility to manage load fluctuations and maintain stability during island mode (the operational mode of standalone or isolated microgrid power equipment, or a multimode inverter or interconnected microgrid disconnected from the primary utility source).

Each DER has unique characteristics that offer specific advantages and disadvantages depending on which primary drivers the microgrid is intended to address. For example, if sustainability and cost optimization are key drivers, a solar photovoltaic (PV) system will likely be included. Preliminary PV sizing is based on the available installation area (roof or ground mount) needed to meet the load's energy requirements.

Evaluating PV system size alongside the site's load profile ensures the PV capacity is neither undersized nor oversized. In many cases, after analyzing PV generation and energy consumption, the design team may determine that introducing additional DERs could provide added benefits.

Additionally, each DER type has characteristics that may align differently with the system's load profile. If additional baseload generation is needed, a fuel cell or prime rated natural gas generator may be appropriate. If the customer requires hot water, a combined heat and power (CHP) system may be advantageous. A battery energy storage system (BESS) is ideal for storing excess PV power for later use (energy arbitrage) or for peak shaving during high demand periods.

Energy modeling is a significant early step in the microgrid design process. Once the energy analysis is complete and the microgrid's load is fully understood, these data are used to select and size the DERs required to meet the system's instantaneous power and overall energy needs. Following this preliminary assessment, the microgrid design engineer begins developing a detailed engineering drawing package. During this detailed design stage, various power systems studies are required to validate DER sizing, confirm system operation, and identify operational risks. **Without these studies, it may be challenging to fully understand the microgrid's power and load flow behavior under both expected and unexpected operating conditions—an issue that becomes even more critical when the microgrid is expected to operate in island mode**.

Recommended power system studies, in addition to the standard studies, may include static load flow or time domain unbalanced load flow (TDULF) analysis, black starting studies, transient stability studies, system grounding analysis, short circuit analysis, and power quality and harmonics studies. Figure 1 below illustrates an example power systems model developed in ETAP, a tool commonly used to perform these analyses. Every major electrical component of the system is modeled, and key parameters are defined for each.

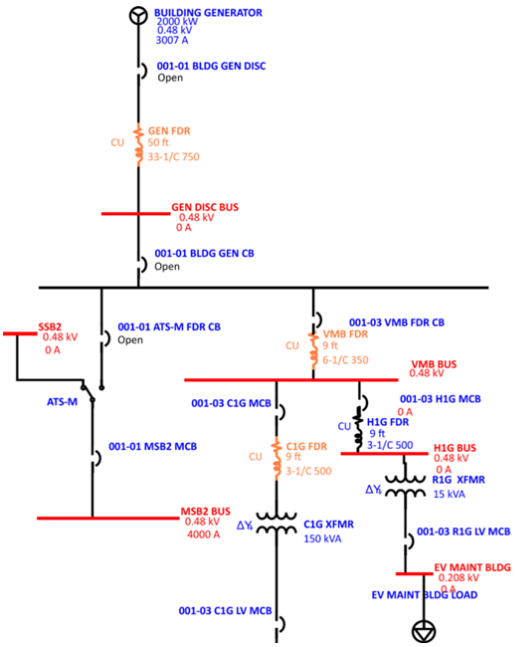


Figure 1

An example of a Power System SLD modelled using ETAP software and setup for performing different power system studies

In the following sections, we explore various power system studies in more detail and explain the benefits of using these studies as part of the overall microgrid design process.

Understanding Power System Studies

Load Flow and Time Domain Load Flow Analysis

Once the engineer determines preliminary DER sizing through energy analysis, a load flow or TDULF analysis becomes necessary to assess power flows under different microgrid operating modes and to understand the grid connected and islanded performance of the DERs. A TDULF analysis offers a more predictable approach than standard static load flow analysis, making it particularly suitable for microgrids where resilience is crucial—mainly because renewable energy sources like solar and wind are intermittent, and BESS units have limited storage capacity.

A TDULF analysis evaluates whether the DERs can support the active power, reactive power, and total energy requirements of the load when the system operates off grid over a defined period. This study uses direct inputs from the energy analysis, including the site's load profile and the DER power generation and dispatch profiles. Analyzing these load and source profiles is critical to performing the TDULF study, enabling the engineer to understand and predict system behavior and finalize preliminary DER sizing.

Figure 2 below illustrates an example load flow analysis for a microgrid system with a BESS serving as the anchor resource for a building operating in island mode. The model displays current magnitudes and directions, voltages at each node, and bus voltages expressed as a percentage of nominal voltage.

Figure 2
Load flow analysis model for a building islanded on BESS IBR

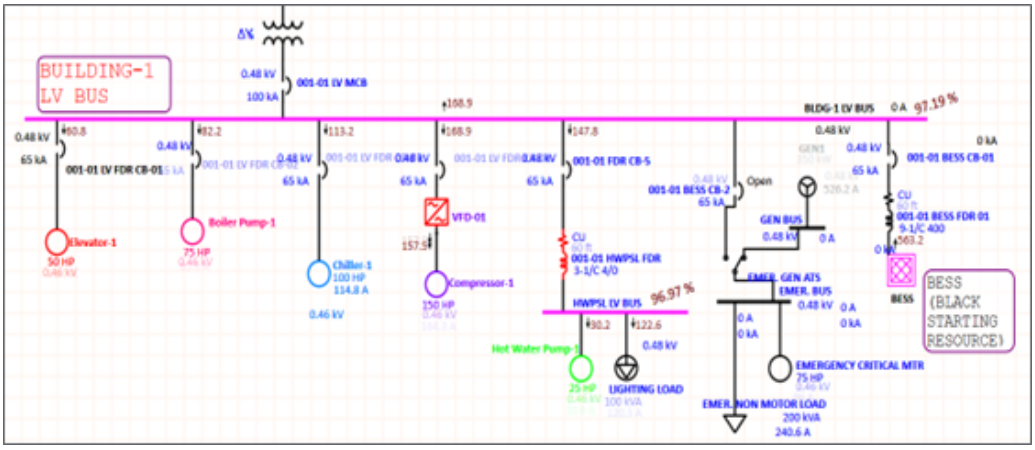
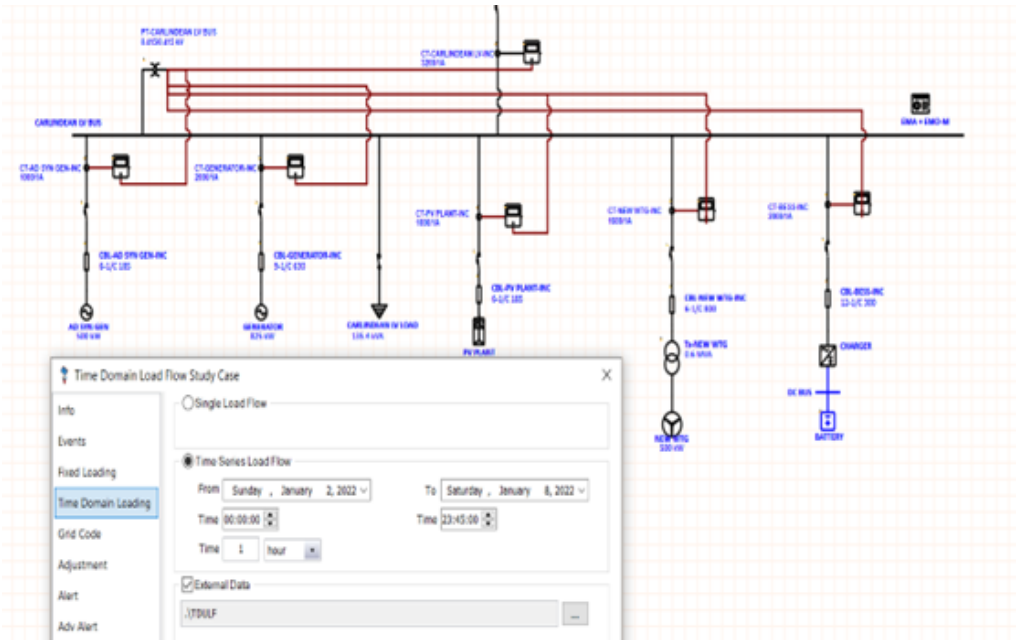


Figure 3 below illustrates a microgrid power system TDULF model. A load profile from an energy model is uploaded to assess how the system responds over time.

Figure 3
TDULF model for a power system



Motor Starting, Transformer Energization, and Black Start Analysis

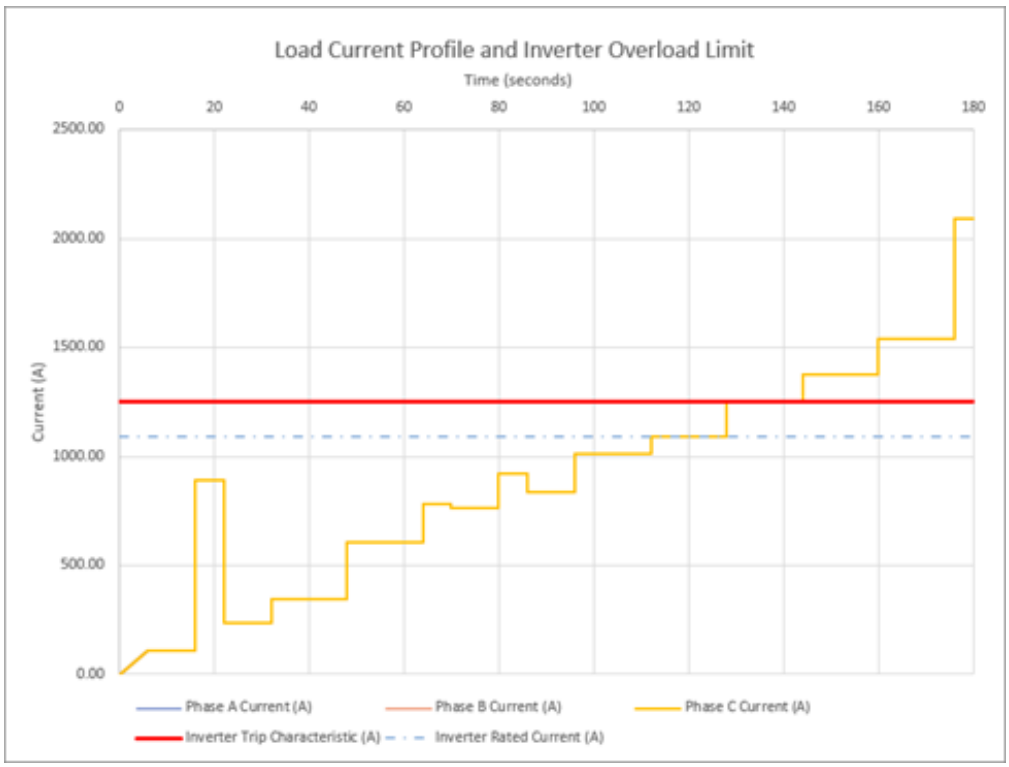
Once the engineer completes the load flow and TDULF studies to understand system power flows, a black start study becomes essential for evaluating whether grid forming DERs can start the power system in island mode. Modern microgrids increasingly rely on current limited inverter based DERs (such as BESS units) to black start large and complex electrical systems without support from other DERs. Unlike conventional backup generators, these inverters have limited capability to handle inrush currents and transient events.

A black start study assesses whether grid forming inverters can meet the worst case inrush requirements created by the site's inductive loads—primarily transformers and motors. Because inductive loads contribute significantly to inrush current during system energization, engineers must evaluate motor acceleration characteristics, develop inrush current profiles, and determine appropriate load sequencing strategies. In many cases, the site may require infrastructure modifications to manage inrush currents, such as switchgear upgrades, changes to downstream equipment, or adjustments to motor starting methods. The microgrid design engineer must carefully specify the overload capacity of current limiting grid forming inverters to ensure a successful black start.

Figure 4 illustrates an example black start analysis for an off grid system using fuel cells and battery storage as anchor resources. The inverter overload limit is plotted alongside the load current profile; the point where the curves intersect indicates a potential inverter trip condition.

Figure 4

Black-starting analysis for an off-grid microgrid



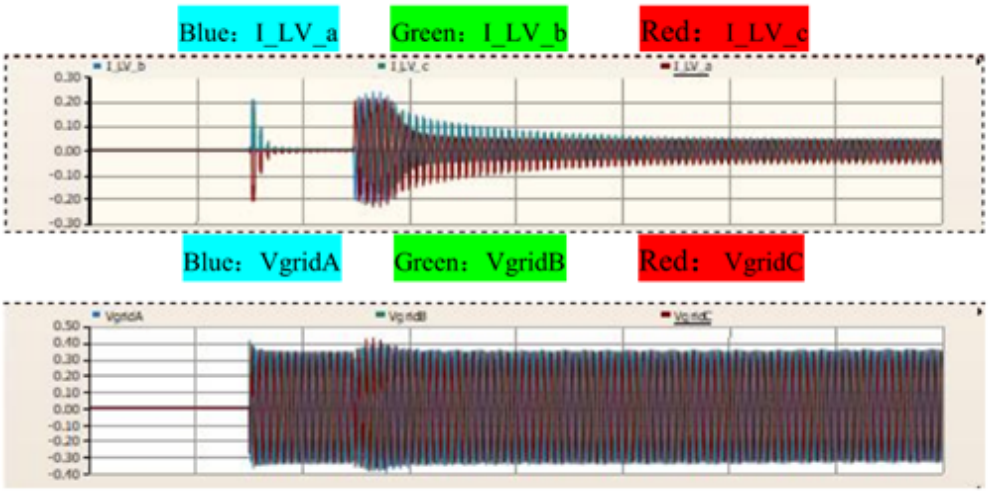
Transient Stability and Transient Analysis

Transient stability studies play a critical role in island-capable microgrids by evaluating how the power system responds to dynamic load changes or the sudden loss of a DER. Rapid fluctuations in frequency, voltage, or power flow can create instability that leads to the loss of key anchor resources. For example, engineers may use transformer-energization studies to determine whether grid-forming inverters can soft-start large, unloaded transformers as part of the overall black-start sequence. These insights allow the engineer to incorporate inrush-mitigation strategies available in modern current-limited inverters, improving overall system resilience.

Operating multimode grid-forming inverters in virtual synchronous generator droop mode may enable seamless transitions between grid-connected and islanded opera-tion under specific conditions. Advanced transient and protection studies help evalu-ate this capability and determine how the system responds to both high- and low-impedance utility faults. These studies also inform the design of proper protection settings. Accurate detection and coordination of voltage and frequency ride-through settings are essential to maintaining stable operation.

Figure 5 shows an example of a transient analysis for an islanded microgrid with a BESS serving as the anchor resource. In this model, the sudden switching of a medium-voltage transformer creates an instantaneous disturbance in the inverter's current and voltage waveforms.

Figure 5
Transient stability analysis of an islanded microgrid



System Grounding Analysis

A system grounding analysis is especially important in microgrid applications because grounding directly affects transient overvoltage behavior and determines key protection requirements. Grounding characteristics depend on the type of power source—utility service, generators, transformers, or static power converters. For systems connected to the grid, the utility typically provides the grounding reference. However, when the system islands, the microgrid must supply its own grounding reference to ensure proper fault detection and protection coordination.

Commercial and industrial systems generally fall into three grounding categories: solidly grounded, impedance grounded (low or high), and ungrounded. Solidly grounded systems allow higher fault currents, which simplifies protection coordination. Impedance grounded systems introduce a resistor or reactor to limit ground fault current. Ungrounded systems have no intentional connection to ground and can exhibit elevated transient overvoltage events during ground fault conditions.

A system grounding analysis is generally necessary to assess how well a microgrid's grounding works when operating in island mode. According to IEEE C62.92.1-6 standards, the coefficient of grounding (COG) is defined as follows:

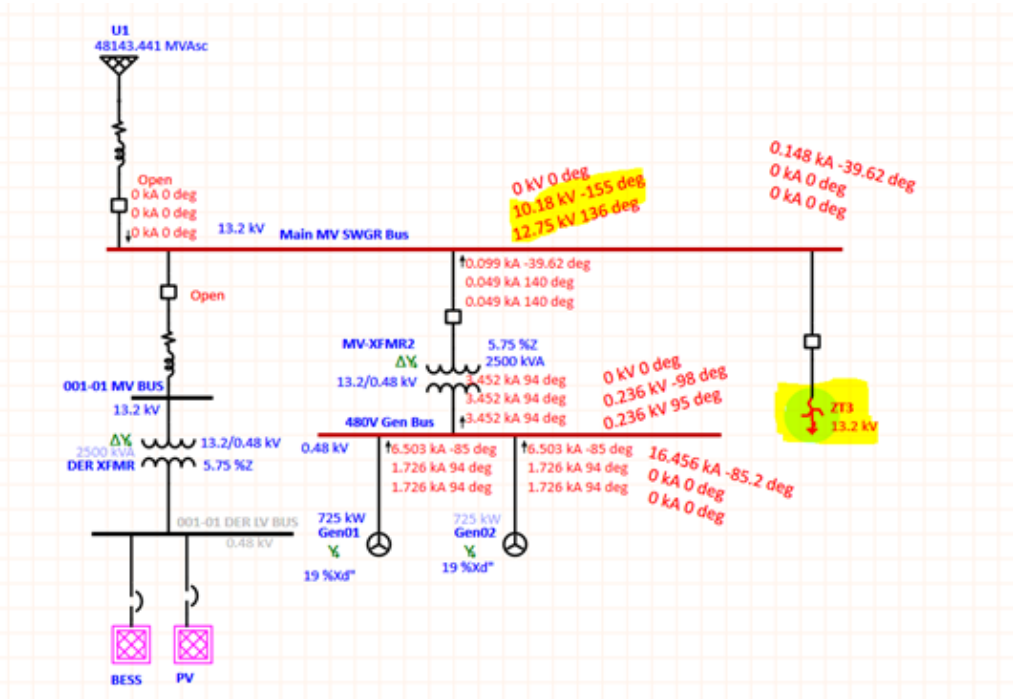
$$\textit{Coefficient of Grounding (COG)} = \frac{\textit{Highest Unfaulted Phase-to-Ground Voltage During a Ground Fault}}{\textit{Phase-to-Phase Voltage with Ground Fault Removed}}$$

A COG below 0.8 typically indicates effective grounding and lower transient overvoltages (TOV) achievable through proper design. Lowering the COG results in lower TOVs, leading to an improved overall system grounding performance.

Figure 6 shows an example analysis in which a single line to ground (SLG) fault on a 13.2 kV bus produces transient overvoltages on the unfaulted phases. In this model, a zig zag transformer with a neutral grounding resistor provides the grounding reference.

Figure 6

System grounding analysis modeling system with utility, PV, BESS, and GEN



Short Circuit Analysis

Any current that exceeds equipment ratings or conductor ampacity is considered an overcurrent. Overcurrents fall into two categories: **overloads** and **faults**. An overload occurs when equipment draws more current than the system can safely supply, creating thermal stress on conductors and equipment. Faults, by contrast, are unintended connections within the system that generate currents far greater than overload conditions. Several fault types exist:

- **Short circuit (bolted fault):** A near zero impedance connection between phase conductors or from phase to ground.
- **Phase to ground fault:** A fault between one phase and ground.
- **Three phase fault:** All three phases faulted together.
- **Phase to phase fault:** A fault between two phases.
- **Impedance fault:** A fault with enough impedance to limit current relative to a true short circuit.
- **Arcing fault:** A fault through an ionized gas (such as air), producing an arc rather than a solid connection.

To quantify a fault, engineers calculate the available fault current at a given location—most commonly the three phase short circuit current. For inverter based DERs, fault contributions are typically limited to **1.0–1.5 p.u.**, depending on the manufacturer.

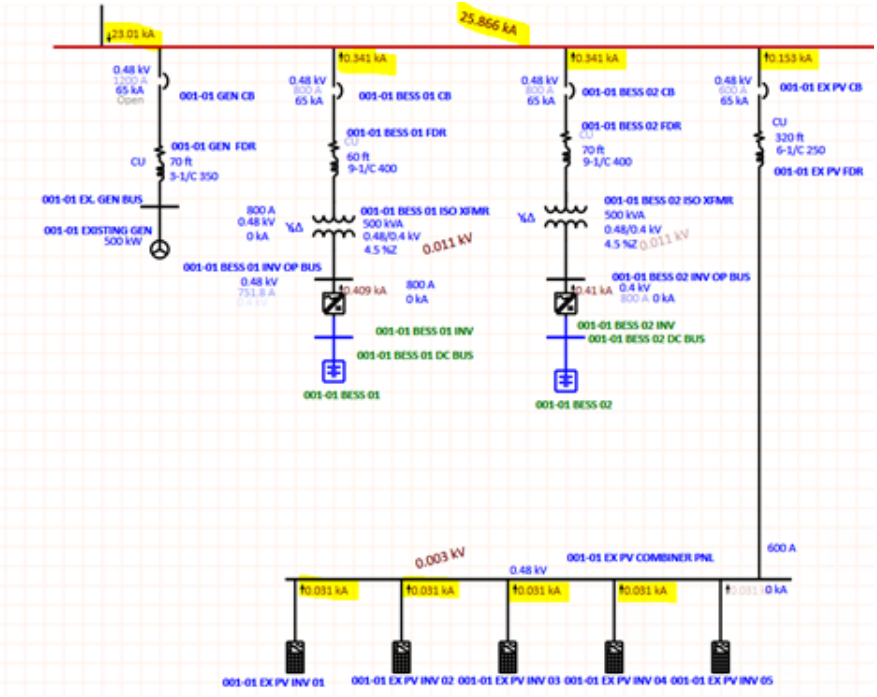
When DERs operate in parallel with the utility in grid connected mode, their fault contributions must be added to the utility's. Similar calculations apply in island mode when inverter based DERs operate alongside generators. Grid connected mode often produces the highest fault currents due to utility contribution, though this is not always guaranteed.

Selective coordination in island mode is more challenging because current limited inverters produce significantly lower fault currents. Their contributions to arcing faults are even smaller due to arc impedance.

Figure 7 illustrates a short circuit analysis in which a three phase fault occurs on the main bus. All sources operating in parallel with the utility contribute to the fault, as highlighted in the model.

Figure 7

Short circuit analysis model - demonstrating a fault situation



Power Quality & Harmonics Analysis

Harmonic distortion is a growing concern in modern power systems because non linear loads disrupt the normal sinusoidal waveform. Power electronic devices—such as drives that rectify AC waveforms—draw non sinusoidal currents. These distorted currents then propagate non linear voltages throughout the system.

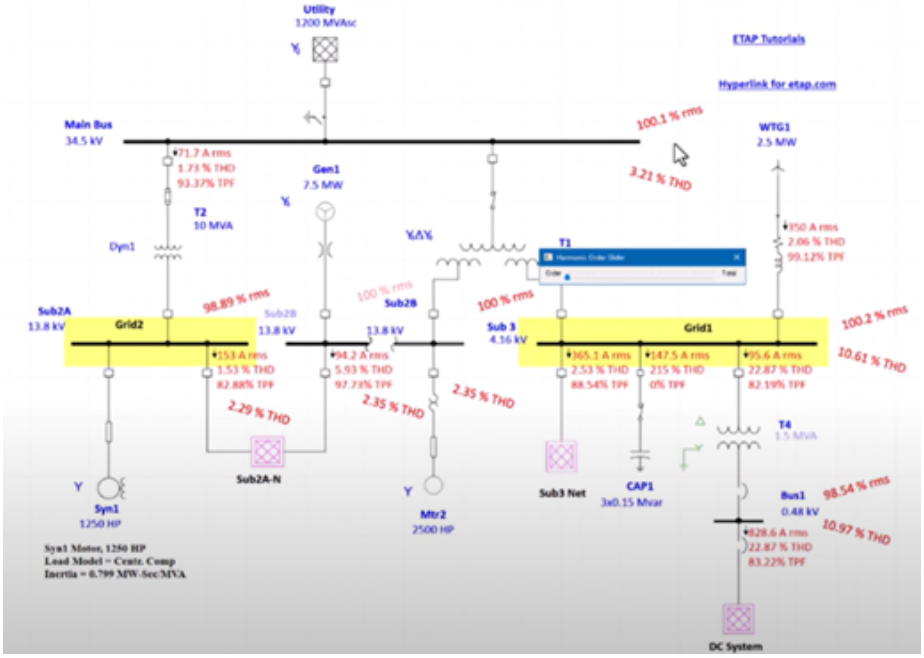
IEEE Standard 519 1992 provides recommended limits for current distortion from customer loads and voltage distortion on the utility supply. Both sets of limits are referenced at the point of common coupling (PCC), where multiple customers connect to the utility system. Facilities with significant non linear loads—including rectifiers, power electronic loads (PELs), and variable frequency drives (VFDs)—should perform a power quality and harmonics analysis to ensure compliance with these limits and to identify potential mitigation strategies.

Poor power quality can severely affect equipment performance. Sensitive medical equipment may malfunction, adjustable speed drives may trip offline, and computers or microprocessor based devices may lose data during voltage interruptions. In extreme cases, such as voltage surges caused by lightning strikes, both power equipment and end use devices may fail altogether. Because modern systems demand high reliability, it is critical to identify and mitigate disturbance sources early to avoid downtime, equipment damage, and safety risks.

A power quality and harmonics analysis evaluates total harmonic distortion (THD) for both current and voltage at key locations in the system. Figure 8 illustrates an example model showing current THD, voltage THD, and power factors at various buses and branches of the single line diagram.

Figure 8

Power quality and harmonic analysis model showing current THD, voltage THD, and power factors



Key Considerations for DER Integration

If a key goal of the project is achieving resiliency through electrical independence from the grid, the design team must carefully select and size grid forming DERs that can act as standalone anchor resources capable of black starting the microgrid and establishing voltage and frequency references during islanded operation. If the electrical grid is available and connected, the grid typically provides the voltage and frequency reference. Based on the size of the grid's generation assets, local DERs usually have minimal influence on grid voltage and frequency when operating in parallel—assuming the grid remains in a stable condition.

During grid instability, the microgrid controller isolates the system from the grid, and a BESS or synchronous generator assumes the role of voltage and frequency reference. Sizing an inverter based DER as a standalone black starting resource depends on multiple factors, including:

- Total system size
- Large step load requirements
- Operational sequencing
- Seasonal load variations
- Unique customer processes

Determining the ideal DER size and configuration may require additional power systems studies to ensure the DER can dynamically respond to load changes, transient events, and system disturbances regardless of when an outage occurs. DER loading analyses and transient studies provide engineers with the data needed to select and size a DER that supports stable and reliable microgrid operation. As stated previously, the microgrid controller isolates the system from the utility upon detecting instability.

Black start and transformer energization studies are essential for validating whether selected DERs are designed and sized appropriately to support system energization and maintain stability during operation. Based on these study results, **additional microgrid controller programming is often required** to manage the energization process through a gradual, multi stage step loading sequence.

Power systems studies for microgrid projects should be integrated with engineering design. These studies are best conducted at each stage of project development, from feasibility through schematic and design development to construction documents. Their results inform system design updates before final issued-for-construction documents are issued. The table below outlines the relevant studies and their typical timing within the engineering design phases.

Power Systems Study	Microgrid Mode of Operation	Typical Design Phase
Energy Analysis	Grid-Connected Islanded	Feasibility, Schematic Design Design Development (30%)
Load Flow Analysis (Static & TDULF)	Grid-Connected Islanded	Design Development (30%, 60%, 90%)
Black Start & Motor Acceleration Analysis	Islanded	Design Development (60%, 90%)
Transient Stability Studies	Islanded	Design Development (60%, 90%)
System Grounding Analysis	Grid-Connected Islanded	Design Development (60%, 90%)
Short Circuit, Time Current Coordination and Arc Flash Analysis	Grid-Connected Islanded	Design Development (90%) Construction Documents (100%)
Power Quality & Harmonics Analysis	Grid-Connected Islanded	Design Development (60%, 90%) Construction Documents (100%)

Power Systems Study	Study Outcome	Relevant Standard
Energy Analysis	Preliminary DER Sizing	IEEE-3810
SC, TCC and AF Studies	Equipment duty/ratings validation and code compliance	IEEE 3002.3, IEEE C37.112, IEEE-1584
System Grounding Analysis	System Grounding Design	IEEE C62.92.1-6
Load Flow/TDULF Analysis	Power Flows on Distribution Equipment	IEEE 3002.2
Motor Starting, Transformer Energization and Black Starting Studies	Design and Sizing of Standalone or MultiMode DERs for Black-Start	IEEE 3002.7
Transient Stability and Transient Studies	System Stability	IEEE C62.82.1, ANSI C37.06, ANSI C37.32, IEEE Std C57.12.00, IEEE Std C57.12.01, IEEE Std C57.13, IEEE P3002.9
PQ and Harmonics Analysis	Power Quality and Harmonic Design	IEEE 519

Conclusion

Power system studies play a critical role in microgrid design. These analyses enable engineers to understand how a microgrid behaves under different operating modes and provide essential data for DER sizing and equipment specification. Load flow studies confirm whether DERs can support the system's active and reactive power requirements, while transient studies reveal how the system responds to sudden disturbances.

Black start studies are strongly recommended for microgrids that operate in island mode, as they evaluate the system's ability to energize loads without utility support. Short circuit and grounding analyses must also be performed to reduce the risk of equipment failures and ensure proper fault protection performance. For facilities with significant nonlinear loads, power quality and harmonics studies may be necessary to identify waveform distortions and determine appropriate mitigation strategies.

Microgrids are complex electrical systems, and these engineering studies provide the insight required to design a robust and resilient solution. By integrating these studies throughout the design process, engineers can ensure the microgrid will operate reliably, support connected loads effectively and meet long term performance expectations.

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